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Command and Control for Large-Scale Hybrid Warfare Systems

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Emerging hybrid threats in large-scale warfare systems require networked teams to perform in a reliable manner under changing mission tactics and ad-hoc reconfiguration of mission tasks and force resources. In this paper, a formal Command and Control (C2) structure is presented that allows for computer-aided execution of the networked team decision-making process, real-time tactic selection, and reliable mission reconfiguration in an ad-hoc manner. A mathematically justified networked computing environment is provided called the Augmented Discrete Event Control (ADEC) framework. ADEC is portable and has the ability to provide the logical connectivity among all team participants including mission commander, field commanders, war-fighters, and robotic platforms. The proposed C2 structure is developed and demonstrated on a simulation study involving Singapore armed forces team with three realistic symmetrical, asymmetrical, and hybrid attack missions. Extensive simulation results show that the tasks and resources of multiple missions are fairly sequenced, mission tactics are correctly selected, and missions tasks and resources are reliably reconfigured in real-time.

Keywords: Command and Control; Discrete Event Systems; Hybrid Warfare; Joint Warfare; Large-Scale Systems Engineering; Rule-Based Systems

1. Introduction

Historically, symmetrical wars are fought between equivalent military forces, where both adversarial sides are state actors similarly organized and configured.[1] Asymmetrical warfare is characterized as radically unconventional, irregular, and unconstrained strategies perpetrated by adversaries of usually non-state actors designed to exploit critical vulnerabilities.[2] Over the past few years, non-state actors have been able to acquire state-equivalent fighting capabilities despite their relative small size. They can now attack stronger adversaries using a fused mix of symmetrical and asymmetrical tactics. To defeat such emerging hybrid threats, armed forces cannot rely solely on military prowess. A blend of well-prepared symmetrical and asymmetrical tactics must be dynamically employed in *hybrid warfare*.[3,4]

The large scale and dynamic nature of modern hybrid warfare systems demands of properly designated commanding officers an exquisite and persistent awareness of their battlefield. They are required to evaluate the potential threats, conduct careful mission planning and resource assignment, and instruct tactic selection and mission reconfiguration in real-time. These requirements desire a powerful command and control (C2) software structure that supports commanders in terms of mission tailoring, force responsiveness and agility, ability to change tactics, and ad-hoc reconfiguration of multiple missions as missions/resources fail or are added.

To the best of our knowledge, while novel C2 structures have been proposed for symmetrical and asymmetrical warfare, minimal work has been done for hybrid warfare. For example, a C2 structure tool was proposed for asymmetrical warfare based on a Discrete Event Control (DEC) framework with simulation study on a realistic military ambush attack.[5] The effectiveness of different C2 approaches was evaluated for asymmetric threats in urban framework involving local and coalition forces, police and other resources.[8] The event analysis for systemic teamwork was applied to military C2 which described system level emergent properties arising from the complex interactions of system components.[9] An approach to evaluate resilience

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14. ABSTRACT

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in C2 architectures was proposed using Petri nets (PNs).[10] Liao in [11] reported an architecture for simulating military C2 using a rule-based approach.

Furthering [5], this paper presents a formal rule-based C2 structure based on novel Augmented Discrete Event Control (ADEC) framework for large-scale hybrid warfare systems. The Boolean matrix formulation of ADEC is portable and easy-to-install on any platform with minimum coding required. As compared to [5], the contributions of ADEC are threefold. First, the capability of tactic selection in real-time is enabled by proposing task sequence selection matrix. Secondly, disjunctive resource assignment is introduced into the rule bases by proposing a disjunctive Resource Assignment Matrix (dRAM). It is verified that disjunctive resource assignment allows for the reduction of model complexity of C2 structure. Finally, ad-hoc reconfiguration of multiple missions' tasks and resources is verified with mathematical rigor. The proposed C2 structure is simulated on a Singapore Armed Forces (SAF) team with three realistic hybrid attack missions and its effectiveness is verified with extensive simulation results.

The rest of the paper is organized as follows. Section 2 give the definition of hybrid warfare and verifies the motivation of this paper. Section 3 details ADEC with mathematical rigor as well as illustrative examples. Section 4 details the proposed C2 structure for large-scale hybrid warfare systems, and Section 5 explains its functionality. Section 6 simulates the proposed C2 structure, and its effectiveness is verified with extensive simulation results on three realistic symmetrical, asymmetrical, and hybrid missions. Finally, our conclusion is summarized in Section 7.

2. Problem Formulation

This section introduces the definition of hybrid warfare using a historical case study and verifies the need for tailoring different tactics hybrid missions.

2.1. *Motivating Example*

Hybrid threat, the combination of asymmetrical tactics and symmetrical force capabilities, is no longer a hypothesis in modern warfare.[6] Hezbollah, a Islamic militant group in Lebanon, is a convincing evidence. During 2006 Israel-Hezbollah war, Hezbollah surprised the world by demonstrating an advanced missile capability which had not been seen for such a small militant group.[7]

On 14 July 2006, INS Hanit, a Saar 5-class corvette, was patrolling in Lebanese waters ten nautical miles off the coast of Beirut. It was damaged on the waterline, under the aft superstructure by an Iranian-supplied anti-ship missile, most probably a Chinese variant of the C-802 Silkworm, fired by Hezbollah. Reportedly, the missile started a fire aboard the ship and critically damaged the corvette's steering capability, requiring it to be towed part of the way back to Israel.

According to the Israeli Navy, the corvette's sophisticated automatic missile defense system was intentionally disabled, while no surveillance or reconnaissance operation was executed *a priori*. These actions were done because of two reasons. First, there were many Israeli air force aircrafts conducting patrolling operations in the vicinity and it was feared that the missile defense system may accidentally be triggered by a friendly aircraft, potentially shooting it down. Secondly, there was no expectation that such an advance missile fighting technology could be possessed by Hezbollah.

2.2. *Hybrid Tactics*

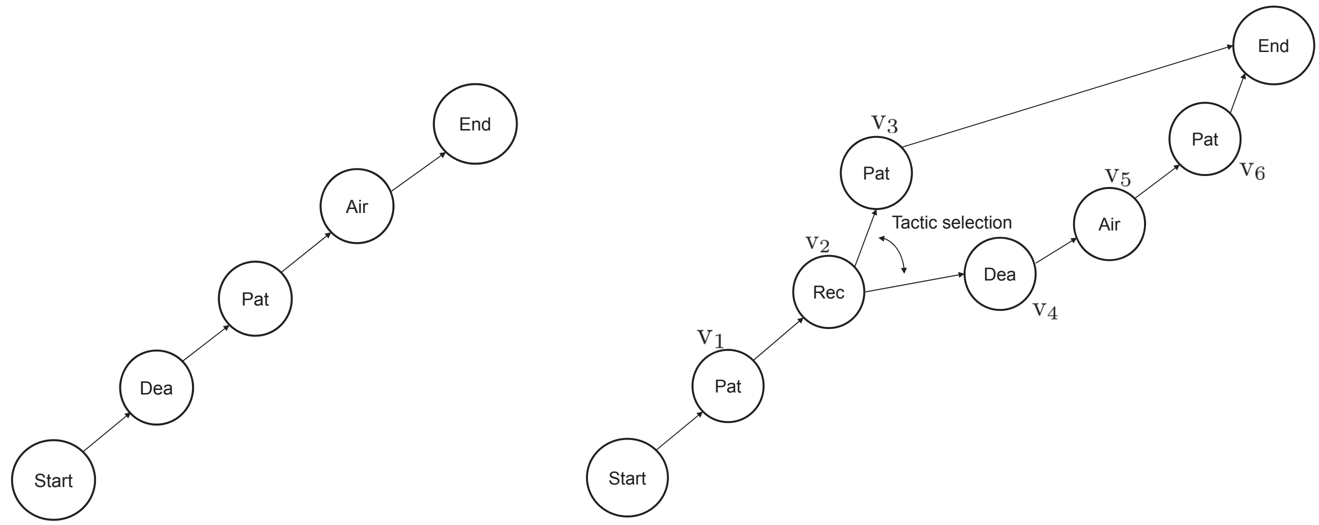
The above example is a warning for advanced armed forces. They cannot afford to overlook force protection and defensive requirements against hybrid threats from small-sized militant groups, who nowadays are able to possess advanced fighting capabilities. This makes hybrid warfare increasingly lethal and complex. Armed forces are necessarily well-prepared with different asymmetrical and symmetrical tactics, and these tactics must be rapidly switched in response to real-time situational information.

Table 1. Task Meaning of Patrolling Mission

Label	Description
Pat	Corvette patrols
Rec	Reconnaissance team explores and reports
Dea	Corvette deactivates defense system
Air	Aircrafts are depolyed

Let us demonstrate again the original patrolling mission as shown in Fig. 1(a), where Israeli corvette and aircrafts patrol freely without anticipation of a symmetrical attack by Hezbollah. The same patrolling mission, yet with hybrid tactics, is shown in Fig. 1(b). The task meaning of this patrolling mission is detailed in Table 1. In particular, INS Hanit first patrols with its missile defense system activated. A reconnaissance team carefully explores the vicinity of patrolling area. Reconnaissance team reports about potential threats to mission commander. If potential threats are detected, INS Hanit keeps patrolling, else missile defense system is deactivated and aircrafts are deployed.

It can be seen that a mission with a number of different tactics has the same number of task sequences. Different task sequences may have similar tasks. Real-time tactic selection requirement is triggered by a task, *e.g.*, reconnaissance and analysis of the adversary's capabilities and selection result is based on the decision of mission commander.



(a) (b)

Fig. 1. Task sequence of patrolling mission with (a) symmetrical tactic and (b) hybrid tactics.

3. Augmented Discrete Event Control

This section details the ADEC framework for C2 structure. Basically, mission task planning and force resource assignment are prescribed by a set of linguistic IF-THEN rules. These linguistic rules are converted to a computer-programmable Boolean matrix formulation.

3.1. *Rule Bases*

We briefly review the conjunctive rule bases in DEC [5] and propose additional real-time tactic selection and disjunctive resource assignment capabilities. A mission comprises of tasks, each of which has some preceding tasks and required resources. Each mission is uniquely associated with some input (triggered) events and a mission output. A mission is described by rules, each of which comprises of IF and THEN parts. In the IF part, preceding tasks, required resources, and input events are predefined. The THEN part specifies the next tasks and the mission outputs. Each rule has the following form:

IF input events happen AND preceding tasks are completed AND required resources are available, THEN next tasks start AND mission output is released.

DEC rules are conjunctive in the sense that only AND operators are present. The presence of choice tasks (tasks performable by alternative resources) has an impact for the rule-based formulation as it increases the number of rules. In particular, a choice task which can be performed by a number of alternative (disjunctive) resources is described by the same number of rules. This impact is serious for modelling large-scale warfare systems which have a significant number of choice tasks.[12]

To enable tactic selection and disjunctive resource assignment, the IF part of each rule in ADEC is modified by

IF input events happen AND *tactic is selected* AND preceding tasks are completed AND all conjunctive resources are available AND *any one of disjunctive resources is available*,

where each choice task is described by only one rule.

Table 2. DEC Rule Bases for Patrolling Mission

Label	Description
x_1	IF u happens AND r_3 is available THEN start v_1
x_2	IF v_1 is completed AND r_1 is available THEN start v_2
x_3	IF v_1 is completed AND r_2 is available THEN start v_2
x_4	IF v_2 is completed AND t_1 is selected AND r_3 is available THEN start v_3
x_5	IF v_2 is completed AND t_2 is selected AND r_3 is available THEN start v_4
x_6	IF v_4 is completed AND r_4 is available THEN start v_5
x_7	IF v_5 is completed AND r_3 is available THEN start v_6
x_8	IF v_3 is completed THEN release y
x_9	IF v_6 is completed THEN release y

For illustration, let us formulate the DEC and ADEC rule bases for the patrolling mission as shown in Tables 2 and 3, respectively. Assume that there are two available reconnaissance teams denoted by r_1 and r_2. We denote INS Hanit and aircraft team by r_3 and r_4, respectively. Let us also denote the mission triggered event by u, mission complete output

by y, asymmetrical and symmetrical tactics by t_1 and t_2, respectively. The tasks are denoted by v_1–v_6 as shown in Fig. 1(b).

Table 3. ADEC Rule Bases for Patrolling Mission

Label	Description
x_1	IF u happens AND r_3 is available THEN start v_1
x_2	IF v_1 is completed AND { r_1 is available OR r_2 is available } THEN start v_2
x_3	IF v_2 is completed AND t_1 is selected AND r_3 is available THEN start v_3
x_4	IF v_2 is completed AND t_2 is selected AND r_3 is available THEN start v_4
x_5	IF v_4 is completed AND r_4 is available THEN start v_5
x_6	IF v_5 is completed AND r_3 is available THEN start v_6
x_7	IF v_3 is completed THEN release y
x_8	IF v_6 is completed THEN release y

From Tables 2 and 3, it can be seen that DEC requires one additional rule as compared to ADEC. In particular, rules x_2 and x_3 of DEC are combined into rule x_2 of ADEC.

3.2. *Tasks, Resources, and Rules*

To map the set of preceding tasks to the set of rules, Task Sequencing Matrix (TSM) F_v is defined such that element $f^v_{ij} = 1$ if task v_j is a preceding task needed to activate rule x_i, and $f^v_{ij} = 0$ otherwise. To map the set of required resources to the set of rules, Resource Assignment Matrix (RAM) F_r is defined such that element $f^r_{ij} = 1$ if resource r_j is a required resource needed to activate rule x_i, and $f^r_{ij} = 0$ otherwise. F_u is an input matrix that maps the set of input events to the set of rules, having element $f^u_{ij} = 1$ if input u_j is required to activate rule x_i, and $f^u_{ij} = 0$ otherwise. Element x_i of the rule vector $\mathbf{x}$ stands for rule $x_i \in X$. If x_i is activated, $x_i = 1$ (true). $\mathbf{v}_c$ is the task completed vector having element $v^c_j = 1$ if task v_j is completed, and $v^c_j = 0$ otherwise. $\mathbf{r}_c$ is the resource available vector having element $r^c_j = 1$ if resource r_j is available, and $r^c_j = 0$ otherwise. $\mathbf{u}$ is the input vector having element $u_j = 1$ if input event u_j occurs, and $u_j = 0$ otherwise. $\mathbf{F}_{ud}$ denotes conflict resolution matrix. Matrix $\mathbf{F}_{ud}$ has as many columns as the number of tasks performed by shared resources. Element $f^{ud}_{ij} = 1$ if shared task v_j is a preceding task needed to activate rule x_i, and $f^{ud}_{ij} = 0$ otherwise. Then, element $u^d_j = 1$ determines the inhibition of logic state x_i (whether rule x_i can be activated).

3.3. *Tactic Selection and Disjunctive Resource Assignment*

We let $\otimes$ and $\oplus$ denote the and/or multiplication and addition, respectively. $\mathbf{C} = \mathbf{A} \otimes \mathbf{B}$ is defined by $c_{ij} = (a_{i1} \wedge b_{1j}) \vee (a_{i2} \wedge b_{2j}) \vee \ldots$, and $\mathbf{C} = \mathbf{A} \oplus \mathbf{B}$ is defined by $c_{ij} = (a_{ij} \vee b_{ij})$. $\wedge$ and $\vee$ are symbols for logical AND and OR operations, respectively.

As discussed in the previous section, each tactic is prescribed by a task sequence. Different task sequences are hence described by independent sets of rules. The split of these sequences is triggered by the same task resulting in some columns of $\mathbf{F}_v$ having multiple "1"s.

To select different task sequences, a task sequence selection matrix $\mathbf{F}_{ut}$ is introduced. Matrix $\mathbf{F}_{ut}$ has as many columns as the number of rules that are activated by the same task. Each column of $\mathbf{F}_{ut}$ contains only one "1" corresponding to the position of the rule that initiates each task sequence's rule set. Element $u^t_j = 1$ if task sequence j is initiated by rule x_i, and $f^{ud}_{ij} = 0$ otherwise. Then, element $u^t_j = 1$ determines the inhibition of logic state x_i (whether rule x_i can be activated). Depending on the way one selects the task sequence vector $\mathbf{u}_t$, different task sequences can be initiated.

Define the state vector for task sequence selection $\mathbf{x}_{ut}$ by

$$\mathbf{x}_{ut} = \mathbf{F}_{ut} \otimes \mathbf{u}_t. \tag{1}$$

The following result is obvious.

Lemma 3.1. (Tactic Selection) The i^{th} rule (*i.e.*, i^{th} row) of (1) is equivalent to

$$x_{ut_i} = u^t_j. \tag{2}$$

The rule element x_{ut_i} is true (equal to 1) if the task sequence that initiated by rule x_i is selected.

To capture the possible assignment of available disjunctive resources to the mission's choice tasks, *i.e.*, to include the OR operators in the IF part, in a convenient and computational-efficient way, define the dRAM which has entry $f^{rd}_{ij} = 1$ if resource r_j can accomplish rule x_i. As such, $\mathbf{F}_{rd}$ maps the resource set R to the rule set X. The dRAM essentially captures information about which available resources can be used for each rule, such that only one of the possible resources listed in row i of $\mathbf{F}_{rd}$ is required to activate rule x_i.

Define the state vector for disjunctive resource assignment $\mathbf{x}_{rd}$ by

$$\mathbf{x}_{rd} = \mathbf{F}_{rd} \otimes \mathbf{r}_c. \tag{3}$$

The following result is obvious.

Lemma 3.2. (Disjunctive Resource Assignment) Define R_{d_i} as the set of resources which **can be used** to fire rule x_i. The i^{th} rule (*i.e.*, i^{th} row) of (3) is equivalent to

$$x_{rd_i} = \bigvee_{r_j \in R_{d_i}} r^c_j. \tag{4}$$

The rule element x_{rd_i} is true (equal to 1) if any one of the resources $r_j \in R_{d_i}$ is available.

3.4. *Logical Equations*

The ADEC state equation is given by

$$\begin{aligned}\overline{\mathbf{x}(k+1)} &= \overline{\mathbf{x}_v(k)} \oplus \overline{\mathbf{x}_r(k)} \oplus \overline{\mathbf{x}_u(k)} \\ &\quad \oplus \overline{\mathbf{x}_{rd}(k)} \oplus \overline{\mathbf{x}_{ud}(k)} \oplus \overline{\mathbf{x}_{ut}(k)}, \end{aligned} \tag{5}$$

i.e.,

$$\begin{aligned}\overline{\mathbf{x}(k+1)} &= \mathbf{F}_v \otimes \overline{\mathbf{v}_c(k)} \oplus \mathbf{F}_r \otimes \overline{\mathbf{r}_c(k)} \oplus \mathbf{F}_u \otimes \overline{\mathbf{u}(k)} \\ &\quad \oplus \overline{\mathbf{F}_{rd} \otimes \mathbf{r}_c(k)} \oplus \mathbf{F}_{ud} \otimes \overline{\mathbf{u}_d(k)} \oplus \mathbf{F}_{ut} \otimes \overline{\mathbf{u}_t(k)},\end{aligned} \tag{6}$$

where k is the loop iteration. The overbar in (5) denotes a vector negation. Given a natural number vector $\mathbf{a}$, its negation is such that $\overline{a_i} = 0$ if $a_i > 0$, and $\overline{a_i} = 1$ otherwise. The properness of (5) is verified as follows.

Theorem 3.3. (Augmented Rule Bases for Task Dispatching, Resource Allocation, and Task Sequence Selection) Denote by V_i the set of tasks that are required as immediate precursors to rule x_i, by R_i the conjunctive set of resources that are all required to fire rule x_i, by U_i the set of inputs that are all required to fire rule x_i, and by R_{d_i} the disjunctive set of additional resources, any one of which can accomplish rule x_i, in addition to all the required resources r_j. The i^{th} rule (*i.e.*, i^{th} row) of (5) is equivalent to

$$x_i = \bigwedge_{\mathrm{v}_j \in V_i} v_j \wedge \bigwedge_{\mathrm{r}_j \in R_i} r_j \wedge \bigwedge_{\mathrm{u}_j \in U_i} u_j \wedge \left(\bigvee_{\mathrm{r}_j \in R_{d_i}} r_j \right) \wedge u_j^d \wedge u_j^t, \tag{7}$$

i.e., rule state x_i is true (equal to 1) if all task vector elements v_j required for rule x_i are true, all resource vector elements r_j required for rule x_i are available, all input vector elements u_j required for rule x_i are true, any of the resources in R_{d_i} is available, the shared-resource conflict (if any) is resolved by assigning the shared resource to rule x_i, and the task sequence that initiated by rule x_i is selected.

Proof. Using matrix operations in the OR algebra, we have

$$\begin{aligned}\overline{x_i} &= \left(\bigvee_{j=1}^{|V_i|} f_{ij}^v \wedge \overline{v_j} \right) \vee \left(\bigvee_{j=1}^{|R_i|} f_{ij}^r \wedge \overline{r_j} \right) \vee \left(\bigvee_{j=1}^{|U_i|} f_{ij}^u \wedge \overline{u_j} \right) \\ &\quad \vee \overline{\left(\bigvee_{j=1}^{|R_{d_i}|} f_{ij}^{rd} \wedge r_j \right)} \vee \left(f_{ij}^{ud} \wedge \overline{u_j^d} \right) \vee \left(f_{ij}^{ut} \wedge \overline{u_j^t} \right). \end{aligned} \tag{8}$$

Successive applications of the de Morgan's theorem yield (9). Now, $f_{ij}^v = 0$ if task v_j is not needed to fire rule x_i. As such $\overline{f_{ij}^v} = 1$ so that for those elements one has $\overline{f_{ij}^v} \vee v_j = 1$ whether the corresponding task element is true or not. On the other hand, $f_{ij}^v = 1$ if task v_j is needed to fire rule x_i. This makes the elements in $\overline{f_{ij}^v} = 0$. One has $\overline{f_{ij}^v} \vee v_j = 1$ if the corresponding task element is true. A similar reasoning applies to f_{ij}^r, f_{ij}^u, f_{ij}^{ud}, and f_{ij}^{ut}. Likewise, $f_{ij}^{rd} = 0$ if resource r_j is not able to accomplish rule x_i. As such, one has $f_{ij}^{rd} \wedge r_j = 0$ regardless whether the corresponding resource element is true or not. Elements $f_{ij}^{rd} = 1$ if resource r_j is able to accomplish rule x_i. One now has $f_{ij}^{rd} \wedge r_j = 1$ if and only if the corresponding resource element is true. As such, the last equation in (9) is equivalent to

$$x_i = \bigwedge_{\mathrm{v}_j \in V_i} v_j \wedge \bigwedge_{\mathrm{r}_j \in R_i} r_j \wedge \bigwedge_{\mathrm{u}_j \in U_i} u_j \wedge \left(\bigvee_{\mathrm{r}_j \in R_{d_i}} r_j \right) \wedge u_j^d \wedge u_j^t. \tag{10}$$

This completes the proof. □

The ADEC's commands to the distributed team in the next iteration are defined by the following output equations

$$\mathbf{v}_s(k+1) = \mathbf{S}_v \otimes \mathbf{x}(k+1), \tag{11}$$

$$\mathbf{y}(k+1) = \mathbf{S}_y \otimes \mathbf{x}(k+1). \tag{12}$$

$\mathbf{S}_u$ is a task start matrix and $\mathbf{S}_y$ is an output matrix. $\mathbf{v}_s$ and $\mathbf{y}$ denote task start vector and output vector $\mathbf{y}$, respectively.

4. ADEC for Large-Scale Warfare Systems

Large-Scale warfare (or usually joint warfare) places priority on the integration of the various service branches of a state's armed forces into one unified command. It is in essence a form of combined forces from army, navy, air, and special forces to work together in joint operations, rather than planning and executing missions separate from each other.[26] Linking systems into large-scale system of systems also allows for the interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance and Reconnaissance (ISR) systems.[24]

$$\begin{aligned} x_i &= \overline{\left(\bigvee_{j=1}^{|V_i|} f_{ij}^v \wedge \overline{v_j} \right) \vee \left(\bigvee_{j=1}^{|R_i|} f_{ij}^r \wedge \overline{r_j} \right) \vee \left(\bigvee_{j=1}^{|U_i|} f_{ij}^u \wedge \overline{u_j} \right) \vee \overline{\left(\bigvee_{j=1}^{|R_{d_i}|} f_{ij}^{rd} \wedge r_j \right)} \vee \left(f_{ij}^{ud} \wedge \overline{u_j^d} \right) \vee \left(f_{ij}^{ut} \wedge \overline{u_j^t} \right)} \\ &= \overline{\left(\bigvee_{j=1}^{|V_i|} f_{ij}^v \wedge \overline{v_j} \right)} \wedge \overline{\left(\bigvee_{j=1}^{|R_i|} f_{ij}^r \wedge \overline{r_j} \right)} \wedge \overline{\left(\bigvee_{j=1}^{|U_i|} f_{ij}^u \wedge \overline{u_j} \right)} \wedge \left(\bigvee_{j=1}^{|R_{d_i}|} f_{ij}^{rd} \wedge r_j \right) \wedge \overline{\left(f_{ij}^{ud} \wedge \overline{u_j^d} \right)} \wedge \overline{\left(f_{ij}^{ut} \wedge \overline{u_j^t} \right)} \\ &= \left(\bigwedge_{j=1}^{|V_i|} \overline{f_{ij}^v} \vee v_j \right) \wedge \left(\bigwedge_{j=1}^{|R_i|} \overline{f_{ij}^r} \vee r_j \right) \wedge \left(\bigwedge_{j=1}^{|U_i|} \overline{f_{ij}^u} \vee u_j \right) \vee \left(\bigvee_{j=1}^{|R_{d_i}|} f_{ij}^{rd} \wedge r_j \right) \wedge \left(\overline{f_{ij}^{ud}} \vee u_j^d \right) \wedge \left(\overline{f_{ij}^{ut}} \vee u_j^t \right). \end{aligned} \tag{9}$$

Large-scale systems complexity arises from the challenging and often-conflicting user requirements, scale, scope, inter-connectivity with different large-scale networked teams and the environment, inter-disciplinary nature of the problems encountered, and the presence of many poorly-perceived system structures.[23] This complexity requires a portable yet adaptable structure that supports multiple mission tailoring, force responsiveness and agility, and ability to reconfigure missions and resources easily in real-time.[25] These emergent behaviours also prompt for the need of a scientific, robust, and holistic framework to conceptualize, design, manage, and implement increasingly complex rules and missions successfully. ADEC has a promising structure wherein control and feedback signals are exchanged among the system's missions in the form of information packages through a communication network.

4.1. *Reduction of Model Complexity*

Lemma 3.2 shows that the usage of ADEC requires less memory as compared to conjunctive tools such as DEC and PNs. It worth noting that the number of rows of matrices $\mathbf{F}_v$, $\mathbf{F}_r$, and $\mathbf{F}_{rd}$, *etc.*, and the number columns of matrices $\mathbf{S}_v$ and $\mathbf{S}_y$ are equivalent to the number of rules of the missions denoted by N.

Recall that the conjunctive DEC needs n rules to describe the starting of a choice task, which can be performed by n different resources. This significantly increases N. In ADEC, a new matrix $\mathbf{F}_{rd}$ is included to keep N minimized, which reduces the system model complexity, especially in large-scale warfare systems.

4.2. *Ad-Hoc Reconfiguration of Multiple Missions and Resources*

Multiple missions sharing the same pool of force resources can be easily modelled and reconfigured by the notion of block matrix. At any time, the various missions of the networked team can be added or removed, each one does not need to know about other missions running in the network, or about the resources required by the other missions. As resources fail or are added, the resource assignment matrices are easily reconfigured in real-time.

For mission i having tasks ordering given by $\mathbf{F}_v^i$ and required resources given by $\mathbf{F}_r^i$ and $\mathbf{F}_{rd}^i$, ADEC prescribes M different missions by

$$\mathbf{F}_v = \begin{bmatrix} \mathbf{F}_v^1 & & \cdots & \mathbf{0} \\ & \ddots & & \vdots \\ \vdots & & \mathbf{F}_v^M & \\ \mathbf{0} & \cdots & & \mathbf{0} \end{bmatrix}, \ \mathbf{F}_r = \begin{bmatrix} \mathbf{F}_r^1 & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{F}_r^M & \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \ \mathbf{F}_{rd} = \begin{bmatrix} \mathbf{F}_{rd}^1 & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{F}_{rd}^M & \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \tag{13}$$

and similarly for the rest of ADEC matrices. $\mathbf{0}$ denotes a null matrix of compatible dimensions. The last rows and columns of $\mathbf{F}_v$, $\mathbf{F}_r$ and $\mathbf{F}_{rd}$ are additional memory spaces on computing software platform for adding new missions and resources, respectively.

Theorem 4.1. (Reconfiguration of Missions) At any time, missions can be programmed or removed without causing blocking to other missions.

Proof. From (6) and (13), we have the state equation of multiple missions written as follows.

$$\begin{bmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^M \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_v^1 & & \cdots & \mathbf{0} \\ & \ddots & & \vdots \\ \vdots & & \mathbf{F}_v^M & \\ \mathbf{0} & \cdots & & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{v}_c^1} \\ \vdots \\ \overline{\mathbf{v}_c^M} \\ \mathbf{0} \end{bmatrix} \oplus \begin{bmatrix} \mathbf{F}_r^1 & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{F}_r^M & \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{r}_c} \\ \mathbf{0} \end{bmatrix} \oplus \ldots, \tag{14}$$

$$\Leftrightarrow \ (15),$$

$$\Leftrightarrow \sum_{i=1}^{M} \hat{\mathbf{x}}^i = \sum_{i=1}^{M} \left(\hat{\mathbf{F}}_v^i \otimes \overline{\hat{\mathbf{v}}_c^i} \right) \oplus \sum_{i=1}^{M} \left(\hat{\mathbf{F}}_r^i \otimes \overline{\mathbf{r}_c} \right) \oplus \ldots, \tag{16}$$

$$\begin{bmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} \mathbf{0} \\ \vdots \\ \mathbf{x}^M \\ \mathbf{0} \end{bmatrix} = \left(\begin{bmatrix} \mathbf{F}_v^1 & & \cdots & \mathbf{0} \\ & \ddots & & \vdots \\ \vdots & & \mathbf{0} & \\ \mathbf{0} & \cdots & & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{v}_c^1} \\ \vdots \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} \mathbf{0} & & \cdots & \mathbf{0} \\ & \ddots & & \vdots \\ \vdots & & \mathbf{F}_v^M & \\ \mathbf{0} & \cdots & & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \mathbf{0} \\ \vdots \\ \overline{\mathbf{v}_c^M} \\ \mathbf{0} \end{bmatrix} \right) \oplus \left(\begin{bmatrix} \mathbf{F}_r^1 & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{0} & \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{r}_c} \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{F}_r^M & \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{r}_c} \\ \mathbf{0} \end{bmatrix} \right) \oplus \ldots \tag{15}$$

where index k is dropped and only $\mathbf{F}_v$ and $\mathbf{F}_r$ are shown for compactness, while the rest of ADEC matrices follow similarly. From (16), it can be seen that the ADEC state equation of multiple missions can be always decomposed to a summations of individual missions' matrices. This implies that missions' tasks and resources having logical OR relation with others. An individual mission can be programmed or removed by causing blocking to other missions. □

Theorem 4.2. (Reconfiguration of Resources) At any time, the resources assigned to the tasks can be removed as resources fail or are added to the network.

Proof. Obviously, adding and removing of resources only affect $\mathbf{F}_r$ and $\mathbf{F}_{rd}$. From (15), we have

$$\mathbf{x} = \left(\begin{bmatrix} \mathbf{F}_r^1 & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{0} & \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{r}_c} \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \vdots & \vdots \\ \mathbf{F}_r^M & \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{\mathbf{r}_c} \\ \mathbf{0} \end{bmatrix} \right) \oplus \ldots, \tag{17}$$

$\Leftrightarrow$ (18),

$\Leftrightarrow$ (19),

$$\Leftrightarrow \sum_{i=1}^{M} \hat{\mathbf{x}}^i = \sum_{i=1}^{M} \left(\hat{\mathbf{F}}_v^i \otimes \overline{\hat{\mathbf{v}}_c^i} \right) \oplus \sum_{i=1}^{M} \sum_{j=1}^{P} \left(\hat{\mathbf{F}}_r^{ij} \otimes \overline{\hat{\mathbf{r}}_c^j} \right) \oplus \ldots, \tag{20}$$

where only $\mathbf{F}_r$ is shown for compactness, while $\mathbf{F}_{rd}$ follows similarly. P denotes the number of force resources. From (20), it can be seen that $\mathbf{F}_r$ and $\mathbf{F}_{rd}$ can be always written as the matrix summations of individual resources. This implies that resources having logical OR relation with others and individual resources can be added or removed. It is assumed that a task is considered uncompleted if its resource is removed during processing. □

5. Functionality of C2 Structure

Let us consider a large-scale warfare system as depicted in Fig. 2, where a distributed networked team is to perform multiple missions. There is one mission commander who overlooks the entire distributed networked team. The whole combat team is divided into several smaller groups, each group is to complete a distinct mission. Each group has one field commander and is assigned a specific sequence of tasks. However, all groups share the same pool of available resources.

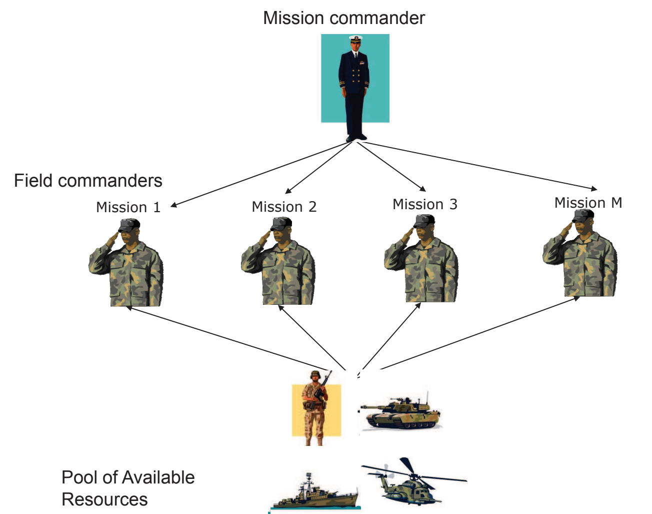


Fig. 2. Centralized and distributed deployment of combat team.

Depending on the deployment scale of the combat team, mission commander can be brigadier general or above

$$\mathbf{x} = \left(\begin{bmatrix} f_r^{11} & \ldots & f_r^{1P} & \mathbf{0} \\ 0 & & 0 & \vdots \\ \vdots & & \vdots & \\ 0 & \cdots & 0 & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{r_1} \\ \vdots \\ \overline{r_P} \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} 0 & \ldots & 0 & \mathbf{0} \\ \vdots & & \vdots & \vdots \\ f_r^{M1} & \cdots & f_r^{MP} & \\ 0 & \cdots & 0 & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{r_1} \\ \vdots \\ \overline{r_P} \\ \mathbf{0} \end{bmatrix} \right) \oplus \ldots \tag{18}$$

$$\begin{aligned} \mathbf{x} = & \left(\begin{bmatrix} f_r^{11} & \ldots & 0 & \mathbf{0} \\ 0 & & 0 & \vdots \\ \vdots & & \vdots & \\ 0 & \cdots & 0 & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{r_1} \\ \vdots \\ 0 \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} 0 & \ldots & f_r^{1P} & \mathbf{0} \\ 0 & & 0 & \vdots \\ \vdots & & \vdots & \\ 0 & \cdots & 0 & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} 0 \\ \vdots \\ \overline{r_P} \\ \mathbf{0} \end{bmatrix} + \right. \\ & \left. \begin{bmatrix} 0 & \ldots & 0 & \mathbf{0} \\ \vdots & & \vdots & \vdots \\ f_r^{M1} & \cdots & 0 & \\ 0 & \cdots & 0 & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} \overline{r_1} \\ \vdots \\ 0 \\ \mathbf{0} \end{bmatrix} + \ldots + \begin{bmatrix} 0 & \ldots & 0 & \mathbf{0} \\ \vdots & & \vdots & \vdots \\ 0 & \cdots & f_r^{MP} & \\ 0 & \cdots & 0 & \mathbf{0} \end{bmatrix} \otimes \begin{bmatrix} 0 \\ \vdots \\ \overline{r_P} \\ \mathbf{0} \end{bmatrix} \right) \oplus \ldots \end{aligned} \tag{19}$$

such as divisional general or lieutenant general, while field commanders are usually lower-ranked sub-unit commanders. For example, consider the brigade combat team, which is a deployable unit of maneuver in many armies. In this case, mission commander is a brigadier general, while field commanders are battalion commanders (lieutenant colonels or colonels). The functionality of C2 structure includes two phases, namely, planning and operation.

5.1. *Planning Phase*

The commanders are assumed to have the know-how to achieve mission desired objectives and are able to convey these instructions linguistically. Mission commander prescribes mission tasks, tactics, triggered events, and desired goal states. Field commanders allocate forces resources for their own mission. The prescribed tasks and resources information are used to construct the linguistic IF-THEN rules.

In rule-based systems,[17,20,21] a rule interpreter software tool is used to match the rule components to other representations. Examples of rule interpreter softwares are CAUSIM[27] and Mobius.[28] Currently, Rule Markup Language (RuleML) is the most popular programming language developed to express linguistic rules in XML for deduction, rewriting, and further inferential-transformational tasks.

In ADEC, the matrices are constructed based on the binary mapping from rules, *e.g.*, mapping of task to rules, resource to rules, and input to rules, *etc.*, respectively. As $\mathbf{F}_v$ is a mapping from tasks to the set of rules and $\mathbf{S}_v$ is a mapping from the rules back to the task space, the rules correspond to the rows of $\mathbf{F}_v$ and the columns of $\mathbf{S}_v$. $\mathbf{F}_{ut}$ and $\mathbf{F}_{ud}$ are prescribed to select different tactics and dispatch shared-resources in real-time. The entire planning phase could be done via graphical user interface softwares on laptops, handheld Personal Digital Assistant (PDA), *etc.* The planning phase is detailed in Fig. 3.

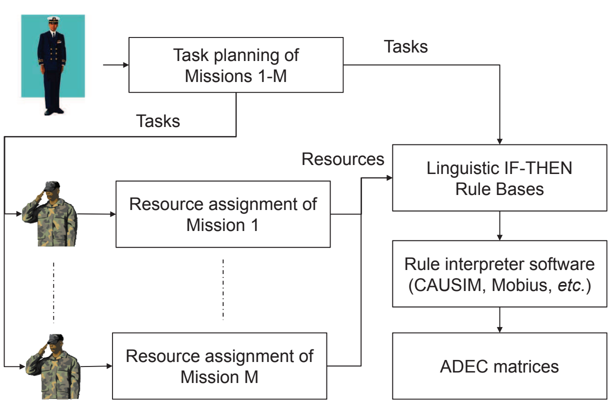


Fig. 3. Planning phase of C2 structure.

5.2. *Operational Phase*

The ADEC will automatically poll active resources for their status at each event update and properly sequence the tasks of all programmed missions, and assign the required resources. Tactic selection and share-resource conflicting requests are quickly and easily handled in real-time by the mean of u_t and u_d. During operation, as resources fail or are added, the $\mathbf{F}_r$ and $\mathbf{F}_{rd}$ is easily reconfigured in real-time to allow uninterrupted mission performance in spite of resource failures. At any time, missions may be programmed into the team or deleted. As missions change or are added, $\mathbf{F}_v$ is easily reconfigured using the notion of block matrix.

The operational phase is detailed in Fig. 4. It can be seen that the ADEC runs on a computer and functions as a feedback controller in real-time and information about team status can be transmitted via a message-passing protocol over many types of communication tools. The first military communication tool was the local network area-based communication automobile designed by the Soviet Union in 1934. The basics of the communications in the beginning were sending and receiving of signals, which were encoded so that the enemy would not be able to get hold of any top secret communication. In the modern world, most nations attempt to minimize the risk of war caused by ex-communication or inadequate communication by pushing the limits of communication technology and systems.

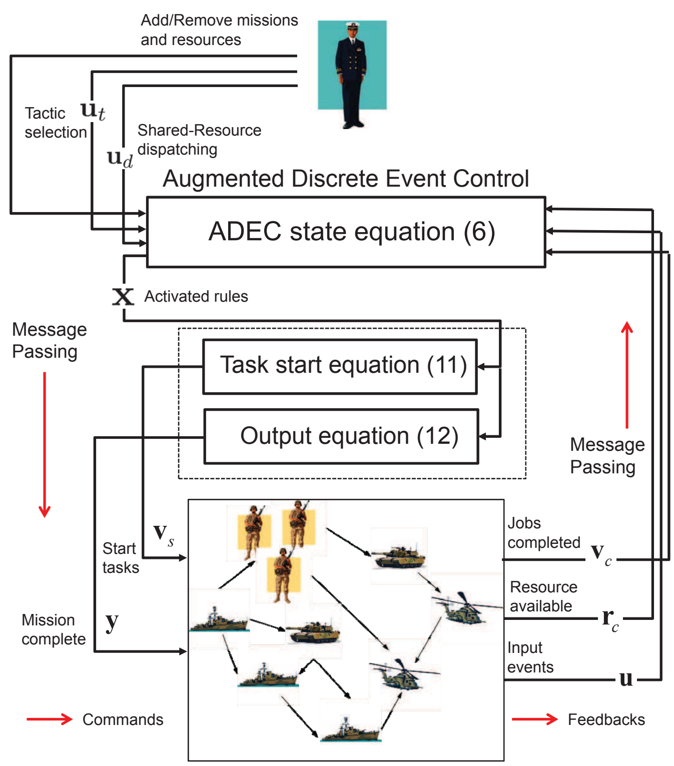


Fig. 4. Operational phase of C2 structure.

The past century has seen many innovations focused on creating advantage in the information domain. The ability to develop and exploit an information advantage has always been important in warfare, hence the timelessness of security and surprise is important principles of war. Examples of innovations that created information advantages in warfare have included couriers on horseback, signal flags, encryption and code breaking, telegraph, wireless radio, aerial reconnaissance and photography, radar, electronic warfare, satellites (communications, reconnaissance), and advances in navigation such as magnetic compass and global positioning system.[18,19] The commands sent by ADEC to distributed networked team could be command inputs into semi-autonomous machine nodes, or in the form of messages for decision assistance over a PDA for human agents, *etc.*

6. Simulation Validation

To illustrate the effectiveness of the proposed C2 structure, three symmetrical, asymmetrical, and hybrid missions are simulated. The proposed C2 structure can be validated as the simulated missions are developed very closely with real-world battles. For example, the Battle of Nasiriyah[14] occurred from 23 March to 2 April 2003 during Iraq War and the Battle of Ganjgal[15] occurred in Afghanistan on 8 September 2009. In addition, linguistic rule-based approaches were often used for the decision support and control of large-scale engineering systems. A rule-based expert system was proposed using linguistic IF-THEN rules and a decision-table-based processor for decision-making.[20] In [21], another linguistic rule-based expert system was proposed where each rule consists of four parts, namely, "Action parameter", "Context", "Condition", and "Action". In military domain, linguistic rule-based approaches were also used for decision-making in C2 structures. In [17], a rule-based C2 structure was proposed to assist the commanders and staffs by insuring the mission information conveys the rules of "Who", "What", "When", "Where", and "Why". The above rule-based approaches are analogous to the IF-THEN rules described in the proposed structure.

6.1. *Mission Description*

In our simulated battle, a SAF team is used as distributed networked combat team. The army is a branch of the SAF responsible for land operations. It is the largest of the three armed services and heavily reliant on a conscript army, comprising mainly of Singapore's operationally ready national servicemen. Typical resources in a SAF team include:[16]

(i) *Singapore Self-Propelled Howitzer 1 Primus*. A self-propelled howitzer armed with a 155 mm howitzer. With the aim of providing better fire support to the armour brigades, this weapon system would require the ability to keep pace with the high tempo of armoured operations, while providing the range, firepower, and accuracy, *etc.*

(ii) *TPQ 37 Radar*. An essential long range weapon locating radar designed for automatic first-round location of weapons firing projectile-type rounds. The primary mission of TPQ 37 radar is to detect and locate enemy mortars and artillery rounds quickly and accurately for immediate engagement.

(iii) *The VHF 900A Series Radio*. A light and small radio, making it easier to for ground troops to carry. The added features of this new radio includes improved physical characteristics, selective call transmission, higher data rates, digital display, and improved security features, *etc.*

(iv) *Headquarters Signals and Command Systems*. The center of the signals formation of the SAF, which is a combat support arm tasked with providing communication on multiple platforms and local networking within the battlefield, as well as with supporting the SAF's third generation transformation efforts by developing the capacity for network-centric warfare. With the radio and communication equipment always maintained at high state of readiness, HQ SIG is to support the C2 requirements of the SAF team. Its present location is at Stagmont Camp, Singapore.

(v) *Singapore Armed Forces Commando Formation*. An offensive unit, it specialises in preemptive operations such as reconnaissance or recce, involving small groups of specially trained soldiers in enemy territory.

(vi) *Armoured Battalions*. An armoured battalion typically includes troop soldiers and tanks. Some tank models currently in service with SAF include the AMX 13-SM1, M113 Ultra Ows, and M113 Ultra 40/50, *etc.*

A SAF team, which consists of three armoured battalions (B1–3) including armed soldiers and tanks, three commando companies (CDO1–3), one self-propelled howitzer coupled with a TPQ 37 radar (Primus), and one headquarters signals and command systems (HQ SIG), is considered in our simulation study. In addition, all soldiers are equipped with VHF 900A series radio (VHF 900A SR).

The simulated SAF team is to perform three realistic offensive missions against three enemy troops (Tr1–3) using symmetrical and asymmetrical tactics. In symmetrical tactic, the SAF team directly attacks the enemy. On the other hand, ambush attack is used in asymmetrical tactic.

Ambush attack is a long-established military asymmetrical tactic, where the aggressors (the ambushing force) use concealment to attack a passing enemy. The simulated battlefield happens in the middle of tropical forest as illustrated in Fig. 4. Three enemy troops (Tr1–3) are moving toward meeting point D from two different roads (A$\rightarrow$D, G$\rightarrow$D, and H$\rightarrow$D). It is known that Tr1 is equipped with heavier defensive systems, and only asymmetrical ambush tactic can be used for Mission 2; while Tr3 is known to be least powerful, and hence symmetrical tactic can be used for Mission 3. The power of Tr2 is not known *a priori*, as such both symmetrical and asymmetrical tactics may

be used. According to SAF's rule, symmetrical tactics can only be used if the enemies' powers are known to be less than one-third of the SAF team. Let us denote by t_1^2 and t_2^2 asymmetrical and symmetrical tactic for mission 2, respectively.

Table 4. Suppressing Enemy Troop 1

Mission 1	Task label	Resource	Task description
Input 1	u^1	–	Tr1 arrives at B
Task 1	v_1^1	CDO1	CDO1 reports to ABN1 and Primus about Tr1 arrival at B
Task 2	v_2^1	B1 or B3	20% goes to A (rear blocking) and 20% goes rockets to destroy Tr1
Task 3	v_3^1	Primus	Primus fires a number of to destroy Tr1
Task 4	v_4^1	CDO1	CDO1 takes measurement and reports to Primus about percentage of damage
Task 5	v_5^1	Primus	Primus fires a number of to destroy Tr1
Task 6	v_6^1	B1 or B2	B1 or B2 at A (20%), C (20%), and station (60%) face-to -face attack Tr1
Output 1	y^1	–	Mission 1 completed

Table 5. Suppressing Enemy Troop 2

Mission 2	Task label	Resource	Task description
Input 1	u^2	–	Tr2 arrives at F
Task 1	v_1^2	CDO2	CDO2 reports to ABN2 and Primus, and mission commanders about Tr2 arrival at F and its power measures
Task 2	v_2^2	B1 or B2	20% of B1 goes to G (rear blocking) and 20% of B1 goes to E (front blocking)
Task 3	v_3^2	Primus	Primus fires a number of to destroy Tr2
Task 4	v_4^2	B1 or B2	B1 or B2 at A (20%), C (20%), and station (60%) face-to -face attack Tr2
Task 5	v_5^2	B1 or B2	Face-to-face attacks Tr2
Output 1	y^2	–	Mission 2 completed

Table 6. Suppressing Enemy Troop 3

Mission 3	Task label	Resource	Task description
Input 1	u^3	–	Tr3 arrives at H
Task 1	v_1^3	CDO3	CDO3 reports to ABN3 about Tr3 arrival at F
Task 2	v_2^3	B3	Face-to-face attacks Tr3
Output 1	y^3	–	Mission 3 completed

Table 7. Rule Bases for Mission 1

Mission 1	Rule label	Rule description
Rule 1	x_1^1	IF (u^1 happens) AND (CDO1 is free) THEN (start v_1^1)
Rule 2	x_2^1	IF (v_1^1 is completed) AND {(B1 is free) OR (B2 is free)} THEN (start v_2^1)
Rule 3	x_3^1	IF (v_2^1 is completed) AND (Primus is free) THEN (start v_3^1)
Rule 4	x_4^1	IF (v_3^1 is completed) AND (CDO1 is free) THEN (start v_4^1)
Rule 5	x_5^1	IF (v_4^1 is completed) AND (Primus is free) THEN (start v_5^1)
Rule 6	x_6^1	IF (v_5^1 is completed) AND {(B1 is free) OR (B2 is free)} THEN (start v_6^1)
Rule 4	x_7^1	IF (v_6^1 is completed) THEN (y^1 happens)

Table 8. Rule Bases for Mission 2

Mission 2	Rule label	Rule description
Rule 1	x_1^2	IF (u^2 happens) AND (CDO2 is free) THEN (start v_1^2)
Rule 2	x_2^2	IF (v_1^2 is completed) AND (t_1^2 is selected) AND {(B1 is free) OR (B2 is free)} THEN (start v_2^2)
Rule 3	x_3^2	IF (v_2^2 is completed) AND (Primus is free) THEN (start v_3^2)
Rule 4	x_4^2	IF (v_3^2 is completed) AND {(B1 is free) OR (B2 is free)} THEN (start v_4^2)
Rule 5	x_5^2	IF (v_4^2 is completed) THEN (y^1 happens)
Rule 6	x_6^2	IF (v_1^2 is completed) AND (t_2^2 is selected) AND {(B1 is free) OR (B2 is free)} THEN (start v_5^2)
Rule 7	x_7^2	IF (v_5^2 is completed) THEN (y^2 happens)

Table 9. Rule Bases for Mission 3

Mission 3	Rule label	Rule description
Rule 1	x_1^3	IF (u^3 happens) AND (CDO3 is free) THEN (start v_1^3)
Rule 2	x_2^3	IF (v_1^3 is completed) AND (B3 is free) THEN (start v_2^3)
Rule 3	x_3^3	IF (v_2^3 is completed) THEN (y^3 happens)

The simulated SAF team is equipped with anti-radar tools so that Tr1–3 are not capable of detecting them. For simplicity but without loss of generality, it is assumed that both uplink and downlink channels of HQ SIG operate at very high bandwidth and are always available. The Primus is placed far away from the battlefield and communicates with the team through the HQ SIG. It is equipped with very high precision lethal attack rockets which is able to destroy enemy targets from distance. The details of three simulated missions are reported in Tables 4–6, respectively. The rule bases are reported in Tables 7–9 for these three missions, respectively. The TSM $\mathbf{F}_v^1$, RAM $\mathbf{F}_r^1$, and dRAM $\mathbf{F}_{rd}^1$ corresponding to the rule bases in Table 6 are given in (18), where the matrix columns are corresponding to the tasks and resources, while the matrix rows corresponds to the rules. Since only asymmetrical tactic can be used for Mission 1, $\mathbf{F}_{ut}^1 = 0$. Next, the matrices TSM $\mathbf{F}_v^2$, RAM $\mathbf{F}_r^2$, dRAM $\mathbf{F}_{rd}^2$, and tactic matrix $\mathbf{F}_{ut}^2$ for Mission 2 in Table 7 are given in (19). Similarly, the ADEC matrices for Mission 3 can be constructed. Then, the overall matrices for three missions in the network are then given in (20). The output matrices for all missions can be derived accordingly. It can be seen that rules x_2^2–x_5^2 of Mission 2 comprise of the execution of asymmetrical tactic, while rules x_6^2–x_7^2 define the execution of symmetrical counterpart. Selection of the tactics depends on the military power of Tr2, which is measured by rule x_1^2. Rule x_2^2 and rule x_6^2 of Mission 2 are activated by the same task v_1^2, resulting in the first column of $\mathbf{F}_v^2$ having two "1"s. As such, $\mathbf{F}_{ut}^2$ has two columns with one "1" in each column, corresponding to the positions of the "1"s in the first column of $\mathbf{F}_v^2$. It is worth noting that tasks v_2^1, v_6^1, v_2^2, and v_5^2 are choice tasks, while others are non-choice tasks.

6.2. *Task and Resource Sequencing*

In Scenario 1, Tr2's military power is more than one-third of the SAF team. As such, both Missions 1 and 2 are performed using the same asymmetrical ambush tactic. The only difference is that Primus has to fire twice in order to reduce or destroy Tr1 because it is known to be armed with heavy defensive weapons a priori. As such, the higher priority is given to Mission 1. When there is a request for the same resource by two tasks (one from each mission), the ADEC will automatically assign resources to complete the tasks in the Mission 1 first. The resulting event traces are shown in Fig. 6.

$$\mathbf{F}_v^1 = \begin{bmatrix} 0\,0\,0\,0\,0\,0 \\ 1\,0\,0\,0\,0\,0 \\ 0\,1\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0\,0 \\ 0\,0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,1\,0 \\ 0\,0\,0\,0\,0\,1 \end{bmatrix}, \; \mathbf{F}_r^1 = \begin{bmatrix} 1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,1\,0\,0\,0 \\ 1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \end{bmatrix}, \; \mathbf{F}_{rd}^1 = \begin{bmatrix} 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \end{bmatrix}, \tag{18}$$

$$\mathbf{F}_v^2 = \begin{bmatrix} 0\,0\,0\,0\,0 \\ 1\,0\,0\,0\,0 \\ 0\,1\,0\,0\,0 \\ 0\,0\,1\,0\,0 \\ 0\,0\,0\,1\,0 \\ 1\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1 \end{bmatrix}, \; \mathbf{F}_{ut}^2 = \begin{bmatrix} 1\,0 \\ 0\,0 \\ 0\,0 \\ 0\,0 \\ 0\,0 \\ 0\,1 \\ 0\,0 \end{bmatrix}, \; \mathbf{F}_r^2 = \begin{bmatrix} 0\,1\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \end{bmatrix}, \; \mathbf{F}_{rd}^2 = \begin{bmatrix} 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0 \end{bmatrix}, \tag{19}$$

$$\mathbf{F}_v = \begin{bmatrix} \mathbf{F}_v^1 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{F}_v^2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{F}_v^3 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}, \; \mathbf{F}_{ut} = \begin{bmatrix} \mathbf{F}_{ut}^1 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{F}_{ut}^2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{F}_{ut}^3 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}, \; \mathbf{F}_r = \begin{bmatrix} \mathbf{F}_r^1 & \mathbf{0} \\ \mathbf{F}_r^2 & \mathbf{0} \\ \mathbf{F}_r^3 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \mathbf{F}_{rd} = \begin{bmatrix} \mathbf{F}_{rd}^1 & \mathbf{0} \\ \mathbf{F}_{rd}^2 & \mathbf{0} \\ \mathbf{F}_{rd}^3 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}. \tag{20}$$

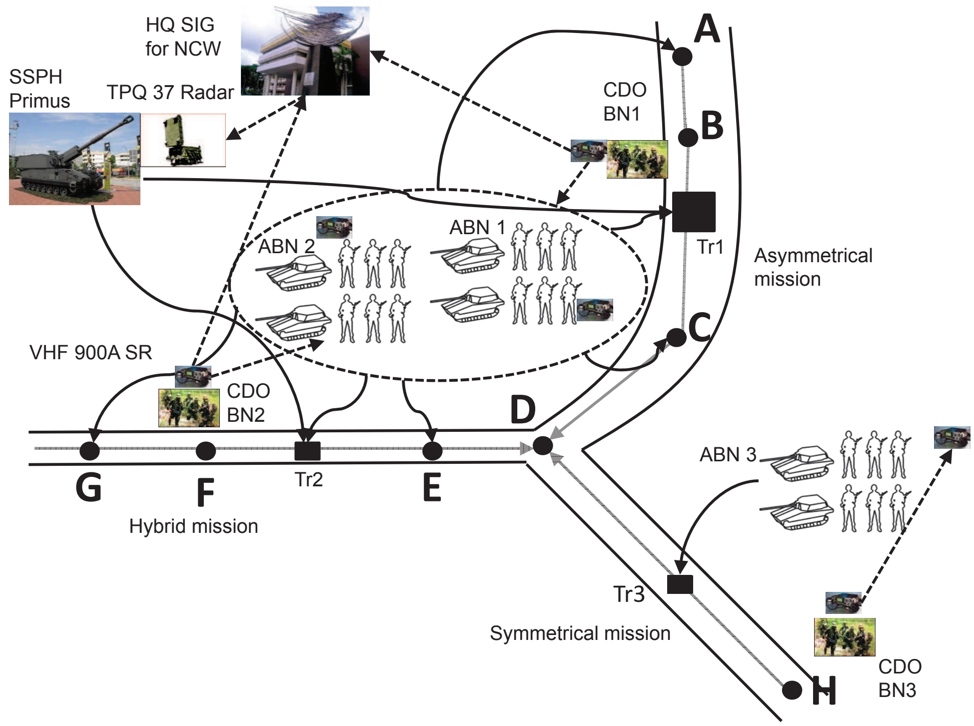


Fig. 5. Simulated battlefield with distributed SAF team performing three missions. Mission 1 uses asymmetrical tactic, Mission 2 uses hybrid tactics, and Mission 3 uses symmetrical tactic. Component figures are taken from (Ministry of Defence Singapore, 2013).

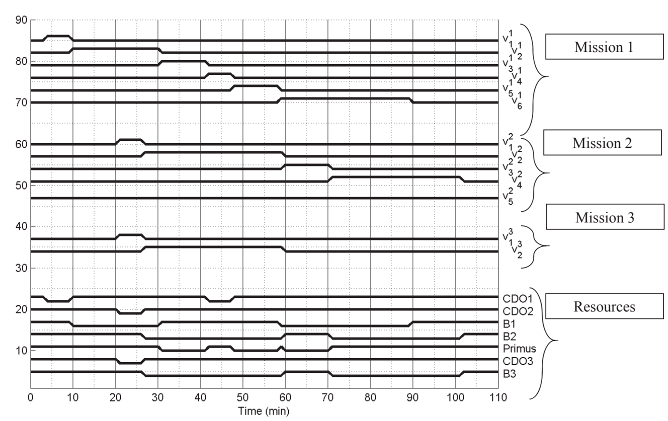


Fig. 6. ADEC sequences mission tasks and resources in Scenario 1.

The processing time of mission tasks are suitably assumed. Tr1 and Tr2 are assumed to arrive at B and F at the 5^{th} and the 20^{th} minutes, respectively. In the task traces, an "up" means a task is being performed or completed but waiting for next task; while in the resource traces, a "down" means the resource is being used. It can be seen from Fig. 6 that both missions request for the same resource Primus at the 48^{th} minute. As priority is given to Mission 1, Primus is assigned to Mission 1 while Mission 2 has to wait. Primus is later assigned to Mission 2 at the 58^{th} minute as Mission 1 releases it.

In Scenario 2, Tr2's military power is less than or equal to one-third of the SAF team. As such, Missions 2 and 3 are performed using symmetrical tactic. The resulting event traces of Scenario 2 are shown in Fig. 7. As seen, the ADEC sequences missions' tasks and resources effectively and the desired goal states are achieved without deadlocks in both scenarios.

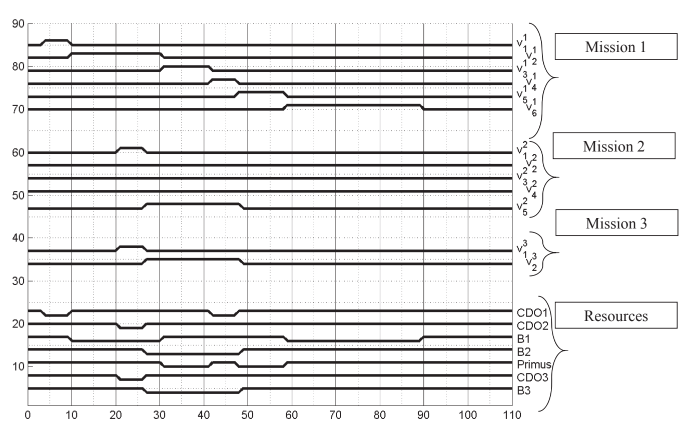


Fig. 7. ADEC sequences mission tasks and resources in Scenario 2.

6.3. *Ad-Hoc Reconfiguration*

We verify that ADEC also guarantees that missions can be added or removed due to termination or changes of missions, and resources can be added or removed as resources fail in an ad-hoc manner while ensuring consistency, completeness, and conciseness in rule-based analysis.[5]

Let us consider Scenario 2 of the previous section. The battle is first assumed to initially consists of Missions 2 and 3, while Mission 1 is added at the 40^{th} minute. Adding Mission 1 is accomplished by adding $\mathbf{F}_v^1$, $\mathbf{F}_r^1$, $\mathbf{F}_{rd}^1$, *etc*, to all ADEC matrices. The resulting event traces are shown in Fig. 8.

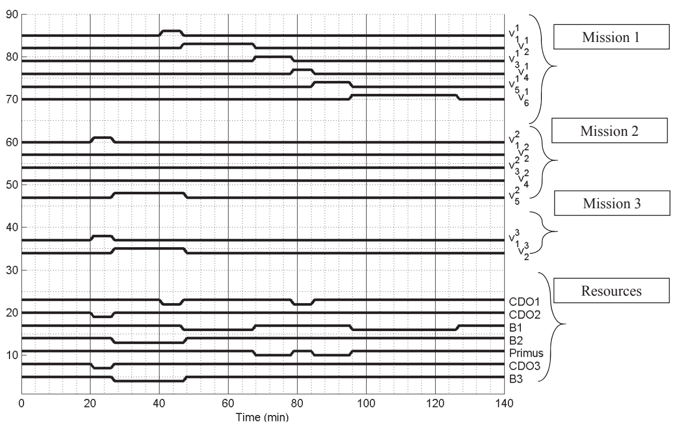


Fig. 8. ADEC adds new mission to the distributed SAF team.

In the second test, the battle is assumed to initially consists of Missions 1–3, and Mission 1 is then removed at the 26^{th} minute. Removing Mission 1 is accomplished by removing $\mathbf{F}_v^1$, $\mathbf{F}_r^1$, $\mathbf{F}_{rd}^1$, *etc.*, out of all ADEC matrices. The resulting event traces are shown in Fig. 9.

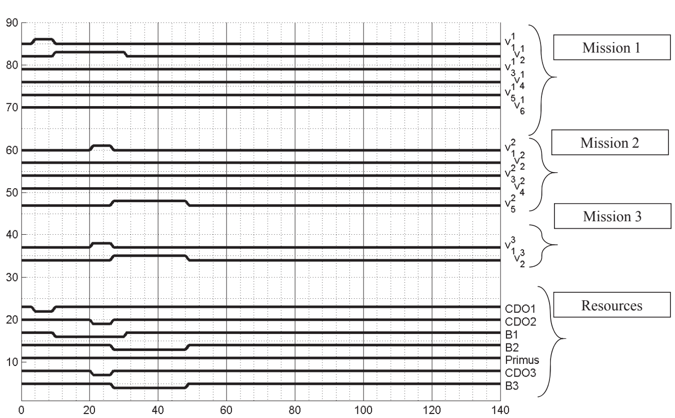


Fig. 9. ADEC removes mission out of the distributed SAF team.

Now, the battle consists of Missions 1–3. Primus is assume to fail at the 44^{th} minute and an additional resource with same capability of Primus, denoted by Primus*, is added at the 45^{th} minute. Adding/Removing of Primus*/Primus is accomplished by adding/removing the corresponding column of $\mathbf{F}_r$ and $\mathbf{F}_{rd}$. The resulting event traces are shown in Fig. 10. As seen, the ADEC sequences missions' tasks and resources effectively without deadlocks when adding and removing of missions and resources.

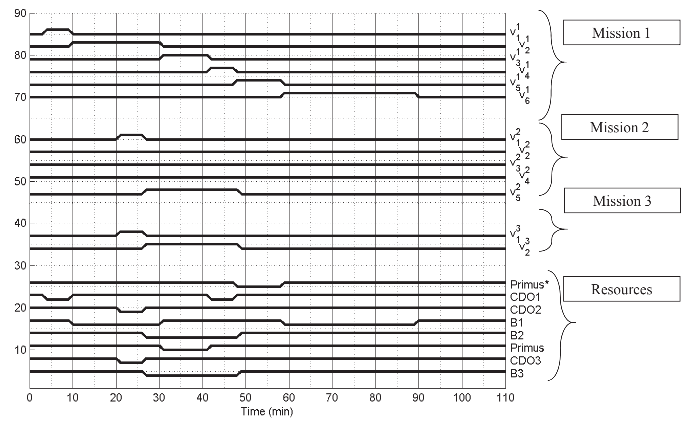


Fig. 10. ADEC adds and removes resource in and out of the distributed SAF team.

7. Conclusion

In this paper, a formal C2 structure was proposed for large-scale hybrid warfare systems based on a mathematically verified networked computing environment called the ADEC framework. The proposed C2 structure is developed and demonstrated on a simulation study involving SAF team with three realistic symmetrical, asymmetrical, and hybrid attack missions. Extensive simulation results verified that the tasks and resources of multiple missions were fairly sequenced, mission tactics were correctly selected in real-time, and multiple missions tasks and resources were reliably reconfigured in an ad-hoc manner.

Beyond military C2, another application of ADEC is operational control and scheduling of nano-satellite swarms for military communications. Nano-satellites deployed in large numbers can provide enhanced capabilities over large latitudinal swaths of the earth. Because they are low cost, they can be added or removed frequently in an ad-hoc manner, which allows rapid technology upgrades, enhances reliability, and reduces manufacturing costs. Nano-satellite swarms are useful in tactical ground operations, humanitarian support, and stability operations. The U.S. Army's Space and Missile Defense Command/Army Forces

Strategic Command has launched the SMDC-ONE program on 8 December 2010 to develop communication nanosatellites.[22]

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